

Local Group HVCs: Status of the Evidence

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Abstract.

The evidence for locating the High Velocity Clouds in the Local Group is summarized and evaluated. Recent measurements of the H α surface brightness and metallicity of a number of HVCs appear to be fatal to the Galactic fountain as a significant contributor to the HVC phenomenon, but not to the existence of the fountain itself. Observations of extragalactic analogues to HVCs remain the *sine qua non* for deciding whether the Local Group hypothesis is viable, but the constraints based on existing surveys appear to be rather weak. MgII quasar absorption lines restrict how many HVC analogues exist at intermediate redshift, depending on where these lines originate. It is concluded that the evidence remains ambiguous, none of the main hypotheses is fully consistent with all of the data, and the Local Group hypothesis remains a viable explanation for the HVC phenomenon.

1. Introduction

Several years ago, the old hypothesis that the High Velocity Clouds (HVCs) are members of the Local Group was revived by Blitz et al. (1999) in a modern cosmological context. The revival of this idea generated some interest in the community because the most formidable objections to it were obviated by the introduction of dark matter, and because the HVCs then played an important role in galaxy formation and evolution. If the idea were right, the HVCs would be imbued with cosmological significance, and could be studied in some detail because they are quite close at hand. Most important, the Blitz et al. (1999) study made a number of specific predictions that could be tested with observations that are relatively straightforward, and it could be learned, in principle, whether the idea is right or wrong in short order.

Some of these tests were carried out, and it turned out that the results, rather than clarifying the issue, added complications, and the nature of the HVCs remains murky. Some of these will be reviewed here to give a flavor of where things stand as of this writing. Space limitations preclude reviewing all of the relevant observational material, but the two other most commonly discussed hypotheses in the recent literature will also be addressed: the Galactic fountain (Shapiro and Field 1976), and stripping from the Magellanic clouds and other dwarf galaxies in the Local Group.

It is worth noting that some authors point out that the HVCs are likely to be a composite phenomenon, with more than one origin, and the discussion of the HVCs ought to take this diversity into account. This view begs the issue on two counts. First, whether or not the HVCs have a single origin, there is likely to be one *dominant* origin for the HVCs responsible for either most of the mass or most of the individual catalogued clouds, and the application of Occam's razor demands that we know what that dominant origin is. Perhaps more important, if the clouds are of Local Group origin, then they almost surely have cosmological significance, and they must have counterparts throughout the Universe. Thus the real question is whether the HVCs play a significant role (past or present) in galaxy formation and evolution, or whether they are simply curiosities related to the Milky Way alone.

2. The Modern Local Group Hypothesis

Of the various pieces of evidence for and against the numerous hypotheses proposed to explain the dominant origin of the HVCs, most are rather weak and ambiguous (e.g. Wakker & van Woerden 1997), and each hypothesis is probably more notable for its weaknesses rather than for its strengths. The modern Local Group hypothesis, however, has the advantage of deriving from a simple dynamical argument that explains the most fundamental aspects of the available data. Using the relatively complete HVC catalogue of Wakker and van Woerden (1991), Blitz et al. (1999) showed that a single compact hypothesis could explain both the spatial and velocity distribution *simultaneously* of HVCs over the entire sky. If the Local Group hypothesis turns out to be incorrect, the competing ideas will have to reproduce both the distribution on the sky and the kinematics of the clouds in a straightforward manner, something none of them has been able to do so far.

The model identifies the HVCs with the earliest structures to form in the Universe, and they are thus necessarily dark matter dominated. Using only the gravity of the Milky Way and M31 (with minor modifications), the model reproduces the observed spatial concentrations on the sky, the shape of the envelope of observed velocities, the amplitude of the distribution and the preponderance of higher absolute velocities in the northern hemisphere. Because the model is so simple, it was possible to make several predictions related to the $H\alpha$ surface brightness of the clouds, metallicities, and the detectability of extragalactic analogues, and to contrast these with the Galactic fountain model, the model favored by most writers on the subject during the 1990s.

3. Tests of the Local Group Hypothesis

3.1. The $H\alpha$ Test

In the late 1990s, $H\alpha$ had been detected toward the largest of the HVCs, and toward the Magellanic Stream (MS – Weiner & Williams 1996; Tufte, Reynolds & Haffner 1998; Bland-Hawthorn et al. 1998). The largest HVCs are close to the Milky Way in all models, and have a mean distance of about 10 – 20 kpc in the LG hypothesis, consistent with direct distance determinations along two lines of

sight (Danly, Albert & Kuntz 1993; van Woerden et al. 1998). There was some debate initially about whether the source of excitation was photoionization from escaping UV radiation from the Galactic plane, or shock heating by passage of the clouds through a tenuous Galactic halo. In the Local Group hypothesis, most of the HVCs are at distances larger than 50 kpc and should exhibit $H\alpha$ surface brightnesses smaller than the weakest of the $H\alpha$ detections regardless of the excitation mechanism. Local Group HVCs will have either lower incident ionizing radiation than the detections for the MS, or they will impinge lower density halo gas, but in either case, the $H\alpha$ emitted from the HVCs should have lower surface brightness.

Several sets of observations were carried out, but the most extensive to be published to date are those of Weiner, Vogel and Williams (2001, this volume) who observed HVCs in the southern hemisphere. It had been expected that most of the HVC detections would either be considerably fainter than the measurements of the MS, if the HVCs are Local Group objects, or much brighter, if they are part of a Galactic fountain. By calibrating the measured surface brightness to a cloud or clouds of known distance, absolute distances to the clouds can be determined by tying the calibration to either a model of the ionizing radiation escaping from the Galaxy or to estimates of the halo density if the HVCs are shock heated.

Judging from Figure 2 of Weiner et al., the situation is much more complex. It had been hoped that the MS, with its known distance, would serve as a calibration for the $H\alpha$ observations, but it turned out that observed fluxes toward the MS vary by two orders of magnitude, making the stream all but useless for calibration purposes. Second, two HVCs, complexes A and M, have measured distances smaller than the MS clouds, yet their $H\alpha$ surface brightness is *fainter* than many of the MS lines of sight. Using a conservative photoionization model and using clouds A and M as calibrators, Weiner et al. conclude that the fainter HVCs they observed have distances inconsistent with an origin in a Galactic fountain. They point out, however, that most of the MS detections are not consistent with the ionization model they use.

More puzzling still is the detection by Weiner, et al. of the HI associated with Sculptor, a dSph galaxy with a large cloud of HI at a distance of 80 kpc. This galaxy should be a relatively good calibrator for the $H\alpha$ measurements because the field-of-view covers a large fraction of the cloud, and because the cloud has a well-determined distance. Many of the $H\alpha$ detections in Weiner et al. are factors of 2 – 5 below the measured surface brightness of Sculptor, suggesting that these clouds have distances of 100 - 200 kpc!

Unfortunately, the interpretation of the $H\alpha$ measurements seem to be fraught with uncertainty, and instead of giving the clean result that had been hoped for, the measurements have raised numerous questions in their own right. So far, measurements have only been made toward southern hemisphere HVCs, which according to the Local Group hypothesis, should be closer than average, and some of them may be contaminated by debris from the MS. Another test would be to observe the small HVCs with high negative velocities within a radian of M31, which should have large distances from the MW and well-determined distances from M31. Where the projected distance from M31 is large, the mea-

sured $H\alpha$ fluxes should be lower, on average, than those observed in the southern hemisphere.

3.2. The Metallicity Test

An unambiguous prediction of the Local Group hypothesis is that the HVCs should have substantially subsolar metallicities. But how low is appropriate? If the HVCs are truly primordial, their metallicities should be zero, but it has been difficult to find *any* intergalactic gas with zero metallicity, especially for gas with column densities like that of the HVCs: the Lyman limit systems. Blitz et al. (1999) suggest values $< 0.1 - 0.3$ solar based on various measurements of intergalactic gas. HVCs originating in a Galactic fountain should have metallicities that are *at least* solar because most come from regions interior to the Solar distance and because they are accelerated by supernovae, stellar winds from O stars, etc. from which they should get higher than solar metallicities. In order to achieve high velocities relative to the LSR, these clouds must not become too well mixed with halo gas, and if this is the case, the high metallicities will be maintained.

Gibson (2001, this volume) summarizes most of the metallicity data published to date (including some of his own unpublished data), and shows that most of the HVCs do indeed typically have metallicities of 0.3 or less. Many of them do not have measurements of the ionized component, and may have metallicities lower than the tabulated value. The highest metallicity cloud in Gibson's list is probably different from all other catalogued HVCs: the original HI detection in the is not confirmed in the Leiden-Dwingeloo HI survey.

The most straightforward conclusion from the metallicity data is that the measurements are inconsistent with the Galactic fountain model, seemingly fatal to it. Even though the number of good measurements are few, no *bona fide* HVC has either solar or supersolar metallicity! Combined with the results from the $H\alpha$ test, it seems that the Galactic fountain model can be ruled out as being a significant contributor to the HVC phenomenon. This does not mean, of course, that the Galactic fountain doesn't exist. Indeed, Blitz et al. give other evidence for the existence of the Galactic fountain, but it does not, apparently play an important role in the HVC phenomenon. The model, it seems, has to be fundamentally altered to fit the data.

Nevertheless, the metallicity data give values somewhat higher than what might be naively expected from the Local Group hypothesis. Furthermore, all but one of the HVCs that have been measured are in the southern hemisphere where there may be some confusion with MS gas; the interpretation of the origin of the metallicities is therefore not unambiguous one way or the other as Gibson (this volume) points out. As is true for the $H\alpha$ test, it would be useful to have some of the small, high negative velocity clouds near M31 measured, but finding suitable background sources is difficult.

3.3. The Extragalactic Analogue Test

In the absence of direct distance measurements, which probe only the nearest clouds, the most direct test of the Local Group hypothesis is to find analogues in other groups similar to the Local Group. The number density of HVC analogues ought to be related to environment, and it is likely that in rich clusters, for

example, the HVC analogues have been, for the most part, accreted. In these systems HVC analogues would still be expected to occupy the outer reaches of a cluster, but perhaps with rather low surface filling fraction.

Estimates of the detectability of HVC analogues requires knowledge of the size and column density (or mass) of the local HVCs. Blitz et al. provided an estimate based on an assumed median distance of 1 Mpc and no correction for beam convolution, which could not be made from the Wakker & van Woerden (1991) data. The size and mass estimates have some flexibility however; the median distance can be as close as 500 kpc without producing difficulties for the dynamical modeling (but requires a larger ratio of dark matter to baryons), and beam smearing is clearly important for the small clouds that make up the majority of the sample (e.g. Wakker & van Woerden 1991; Braun & Burton 1999). Assuming a distance of 700 kpc and an estimate of the effect of beam smearing from the data of Hartmann & Burton (1997), a typical HVC has a diameter of about 14 kpc, a typical HI mass of about $5 \times 10^6 M_{\odot}$, and a similar ensemble of HVCs in a distant group has a surface filling fraction on the sky of about 1%.

Even with the earlier, larger size and mass estimates, direct detection of HVC analogues by either emission line or absorption line experiments would be difficult, as pointed out by Blitz et al. because of the low surface filling fraction, and because of beam dilution, except for relatively nearby groups. Nevertheless, several sensitive HI surveys have been made, and the most sensitive of these, the Arecibo HI Sky Survey (AHISS; Zwaan et al. 1997), failed to detect any HVC analogues (Zwaan & Briggs 2000). These authors argued that they should have detected 70 HVCs around groups and about 250 HVCs around galaxies in their survey based on the sizes and masses given by Blitz et al. (1999). They concluded that if the HVCs are indeed related to the Milky Way, they must have distances < 200 kpc; their conclusions cast considerable doubt on the Local Group hypothesis.

The Zwaan & Briggs result was, however, recently reevaluated by Braun & Burton (2001), who find several fundamental flaws. First, the assumed noise of the AHISS was found to be somewhat underestimated and the sensitivity somewhat overestimated. Second, most of the groups and individual galaxies Zwaan & Briggs considered are too far away and the covering fraction of HVC analogues is too small for the AHISS non-detections to place significant limits on the number of HVC analogues in these systems. Third, Zwaan & Briggs included any field galaxy that fell within 1 Mpc of the AHISS survey strip in their analysis, but Braun & Burton (2001) argue reasonably that distance is too high by about an order of magnitude. When Braun & Burton (2001) make the necessary corrections, they find only one group, the NGC 628 group, within a distance range that could put significant constraints on the number of extragalactic HVC analogues. Yet the number of clouds in that group that could be present and still be consistent with the Zwaan & Briggs non-detections is comparable to to the number expected to be in the Local Group from the catalogue of Wakker & van Woerden (1991)! Braun & Burton (2001) find a similar result when they considered individual field galaxies. Thus, the non-detections in the AHISS survey do not place useful constraints on HVC analogues in other systems. The reason for the difference from the Zwaan & Briggs analysis is that Braun &

Burton (2001) show that only in the nearest galaxies and groups are mass limits sufficiently sensitive and in these groups the survey samples only a small fraction of the relevant projected area of the sky. Burton & Braun (2001) go further and examine all of the relevant HI surveys, and find that none of those published to date put a limit the number of HVC analogues in other systems inconsistent with a generalization of the Local Group hypothesis.

To overcome some of the difficulties with using the AHISS, Zwaan (2001) did a targeted survey of six galaxy groups with the Arecibo telescope. By doing Monte Carlo simulations of HVC analogues within these groups, he concluded that between 6 and 28 sources should have been detected, depending on the assumptions, if the number of HVC analogues in each group is 100. Zwaan did detect several sources, but argued that none are HVC analogues. However, in none of the groups is the fractional surface area covered by the observations larger than 0.005. Based on a surface filling fraction of 0.01 in each group, the total number of detections expected in Zwaan's data is two, just the number of HI clouds he detects that are not associated with a galaxy. These detections may be analogues of the nearby complexes A, C and M. In any event, the number of extragalactic HVC analogues is still poorly constrained by the observations.

Yet, even if none of the HI surveys to date can rule out that HVC analogues are seen in other groups, shouldn't it be possible to find the largest such systems in some other groups? Why hasn't the upper end of the HVC luminosity function been detected in other systems? Part of the answer is that the HVC luminosity function cannot be determined from the data at hand because individual HVC distances are not known. On the other hand, at least one HVC analogue has now been identified in the nearby Universe, with a mass of $1.7 \times 10^7 M_\odot$, a diameter of 15 kpc at an estimated distance of 3.2 Mpc, and no stars to a limiting $\mu(B) \sim 27$ mag arcsec⁻² (Kilborn et al 2000). The distance, based on a heliocentric velocity of 450 km s⁻¹ and the assumption that it is in Hubble flow, is rather uncertain. Thus, at least one HVC analogue of mass and size within the range expected, and incidentally requiring a large amount of dark matter to be stable, has been identified, but where are the others? Blitz et al. (1999) catalogued a number of high mass HVC analogues from the literature, but because of their proximity to massive galaxies, it cannot be certain that these are not tidal features, though in most cases, they do not have tidal morphologies.

One solution is to look at the Sculptor group, the group nearest the Milky Way at a distance of about 1.5 Mpc. Many of the higher mass clouds should have been detected in the HIPASS Survey, and in the southern extension of the Leiden-Dwingeloo HI survey (Arnal et al. 2000). However, the Sculptor group is situated behind the Magellanic Stream and is confused in velocity at many positions with it. Nevertheless, the velocity dispersion of the group is much larger than that of the HI in the MS and should be separable from it. A tentative confirmation of an increased HI velocity dispersion in the direction of Sculptor was published by Putman (2000), but the data have not yet been analyzed in detail. The HIPASS survey has not been corrected for stray Galactic radiation in the sidelobes and so is useful only at velocities beyond those of the Galactic emission. With its larger beam, the Villa Elisa HI survey has a somewhat lower mass sensitivity than HIPASS, but it can be corrected for sidelobe contamination and will be a good test. Not finding HVC analogues in the Sculptor group, if

these surveys are as sensitive as are claimed, would likely prove fatal for the Local Group hypothesis.

3.4. The MgII Test

If HVC analogues populate groups of galaxies like the Local Group, they should occasionally be seen in quasar absorption lines, since these lines of sight are sensitive to much lower HI column densities than 21-cm emission lines. Recently, Charlton, Churchill & Rigby (2000) examined the statistics of moderate redshift MgII and Lyman limit absorbers in QSO absorption lines as a probe to see what sort of contribution might come from HVC analogues.

Stripped to its essentials, the argument made by Charlton et al. is as follows. Strong MgII absorbers are found in 58 systems toward 51 quasars in a survey by Steidel, Dickinson & Persson (1994). However, all but 3 of the 58 absorbers have identified galaxies with a coincident redshift within $40h^{-1}$ kpc of the quasar, so presumably all but 5% of the strong MgII absorbers are from the galaxies, which are generally normal and bright ($L \geq 0.1L^*$). This leaves only a small contribution possible from a population of HVC analogues. However, the covering fraction of HVC analogues, per galaxy group, is equal to $N_{HVC}/N_{gal} \times (R_{HVC}/R_{gal})^2$, where N_{HVC} and N_{gal} are the number of HVCs and galaxies within a particular group, and where R_{HVC} and R_{gal} are mean radii of HVCs and galaxies in the groups. For the values of these quantities of 300, 4, 7.5 kpc and 40 kpc respectively, the HVC covering fraction is about 2.5 times that of galaxies. Thus either the surface filling fraction of MgII absorbing gas is $\ll 1$, or the Local Group hypothesis overpredicts the number of MgII absorbers. Similar arguments are made about weak MgII absorbers, and Lyman Limit systems.

This simple, persuasive argument has at least one serious weakness. The criterion for positional coincidence in the Steidel et al. (1994) survey is that the galaxy be within $40h^{-1}$ kpc, or about 60 kpc, and the required velocity coincidence is several hundred km s^{-1} , limited primarily by the precision of the galaxy redshifts. The impact parameter is, however, much larger than a typical HI radius even for a large galaxy. Furthermore, Dickinson & Steidel (1996) find that the absorbers are consistent with a *spherical* distribution in the galaxies, rather than a disk-like distribution. Thus it may be that a substantial fraction of the MgII absorbers are due not to the galaxy itself, but to HVCs along the line of sight, either close to the galaxies as an HVC is being accreted or in the intergroup gas of a parent galaxy. If, for example, this is the case in about half the galaxies, then the Charlton et al. constraint is considerably softened, and the statistics of the MgII absorbers rather than providing a strong constraint against the Local Group hypothesis, could instead provide important support for it.

4. Other Distance Indicators

The availability of direct distance determinations remains disappointingly sparse. However, Braun & Burton (2000) and Brüns, Kerp, & Pagels (2001) have suggested a new way to determine the distances to the HVCs. The basic idea is that in some cases, both the column density and angular diameter of an HVC are well

measured quantities; aperture synthesis observations sometimes make it possible to identify dense clumps in the HVCs. If it is possible to determine the density of the clumps independently, one can solve directly for the distance. Braun & Burton (2000) have used this technique to estimate the distances to several clouds which are typically in the range of several hundred kpc, strengthening the Local Group hypothesis.

Both Braun & Burton (2000) and Brüns et al. have found clumps with linewidths so narrow that it is possible to get an upper limit to the kinetic temperature of the clumps. If the depth of the clump is comparable to its dimensions on the sky, then its density and therefore internal pressure depends only on its distance. If the external pressure is known, then the distance to the clump can be found under the assumption of pressure equilibrium. The difficult part is getting a measure of the external pressure. Braun & Burton (2000) use an extension of a model of Wolfire et al. (1995), but it is unclear whether the model is applicable to the very low pressures of the intergalactic medium. The derived distances are therefore highly model dependent. Brüns et al. take a different tack and assume that the clumps are virialized, an unjustified assumption for deriving the distance. If the assumptions in both of these models are correct, then the distance determinations are probably sound. However, because the estimates are so dependent on the assumptions, they cannot be used as primary distance discriminants for the HVCs.

5. Summary Evaluation

Of the four tests, two, the metallicity test and the $H\alpha$ test appear to rule out the Galactic fountain as contributing significantly to the HVC phenomenon. This leaves the Local Group hypothesis, and either tidal or ram pressure stripping of gas from Local Group galaxies as the main contenders for being the dominant origin of the HVCs. It could be that some of the HVCs are debris from the MS, but clouds that are stripped from the Magellanic Clouds should lie on a great circle with the MS, and most of the HVCs do not. No other galaxies in the Local Group have been identified as potential progenitors for these clouds, because, if the HVCs are not self-gravitating, they must be rather short lived. Thus although some authors have suggested that the HVCs might be tidal remnants (e.g. Wakker et al. 1999), there is neither kinematic nor dynamical evidence to support this idea.

Searches for extragalactic HVC analogues have not placed strong constraints on the number of HVCs with mean diameters of 15 kpc and mean masses of $5 \times 10^6 M_\odot$. However, the larger mean size and mass originally estimated by Blitz et al. (1999) is difficult to sustain in view of the results of the HI surveys of Zwaan & Briggs (2000) and Zwaan (2001), if the number of HVCs is as large as that implied in the catalogue of Wakker & van Woerden (1991). However, it is also possible, that many objects identified as tidal features in groups of galaxies and even near field galaxies, are actually extragalactic HVC analogues and do not have their origins in galaxies. These may plausibly be extragalactic analogues of complexes A, C and H, the HVCs closest to the Milky Way and probably in the process of being accreted. After all, if complex C were viewed from, say, M81 with telescopes comparable to what we have been using, its long

stringy morphology in close proximity to the MW would be very suggestive of a tidal feature.

The dynamical evidence remains the best evidence for the Local Group hypothesis, and although the various tests are not in obvious contradiction to it, neither do they provide strong confirmation. Rather, the H α observations remain puzzling, and the MgII absorbers provide an important constraint only if the gas associated with these systems is much more extended and is distributed spherically, both of which are very different from the gas seen in spiral galaxies at zero redshift. Although the metallicities measured so far fall within the range predicted by Blitz et al. (1999), they do remain uncomfortably high, higher than typical metallicities measured in LG dwarf spheroidal galaxies, for example. Nevertheless, if the Local Group hypothesis turns out to be incorrect, it will be challenging for an alternate hypothesis to produce a good simple explanation for both the kinematic data and the spatial distribution of the HVCs, which has been where other ideas have always been the weakest.

References

- Arnal, E.M., Bajaja, E., Larrate, J.J., Morras, R. & Pöppel, W.G.L. 2000, A&AS, 142, 35
- Bland-Hawthorn, J., Veilleux, S., Cecil, G.N., Putman, M.E., Gibson, B.K. & Maloney, P.R. 1998, MNRAS, 299, 611
- Blitz, L., Spergel, D.N., Teuben, P.J., Hartmann, D. & Burton, W.B. 1999, ApJ, 514, 818
- Braun, R. & Burton, W.B. 1999, A&A, 341, 437
- Braun, R. & Burton, W.B. 2000, A&A, 354, 853
- Braun, R. & Burton, W.B. 2001, astro-ph-0004033
- Brüns, C., Kerp, J. & Pagels, A. 2001, A&A, in press (astro-ph 0103119)
- Charlton, J.C., Churchill, C.W. & Rigby, J.R. 2000, ApJ, 544, 702
- Danly, L., Albert, C.E. & Kuntz, K.D. 1993, ApJL, 416, L29
- Gibson, B.K. 2001, this volume
- Hartmann, D. & Burton, W.B. 1997, Atlas of Galactic Neutral Hydrogen, (Cambridge: Cambridge University Press)
- Kilborn, V.A. et al. 2000, AJ, 120, 1342
- Putman, M. 2000, PASA, 17, 1
- Shapiro, P.R. & Field, G.B. 1976 ApJ, 205, 762
- Steidel, C.C., Dickinson, M., & Persson, E. 1994, ApJL, 437, L75
- Dickinson, M. & Steidel, C.C. 1996, in *New Light on Galaxy Evolution*, Bender, R. & Davies, R.L., eds, Kluwer: Dordrecht, 295
- Tufte, S.L., Reynolds, R.J. & Haffner, L.M. 1998, ApJ, 504, 773
- van Woerden et al. 1998, in *The Local Super Bubble*, ed. D. Breitschweidt, & M. Freiberg, (Berlin:Springer), 467
- Wakker, B.P. & van Woerden, H. 1991, A&A, 250, 509
- Wakker, B.P. & van Woerden, H. 1997, ARAA, 35, 217
- Wakker, B.P. et al. 1999, Nature, 402, 388
- Weiner, B.J. & Williams, T.B. 1996, AJ, 111, 1156
- Weiner, B.J., Vogel, S. & Williams, T.B., 2001, this volume

- Wolfire, M.G., McKee, C.F., Hollenbach, D. & Tielens, A.G.G.M. 1995, ApJ, 453, 673
Zwaan, M.A., Briggs, F.H., Sprayberry, D. & Sorar, E. 1997, ApJ, 490, 173
Zwaan, M.A. & Briggs, F.H., 2000, ApJ, 530, L61
Zwaan, M.A. 2001, MNRAS, in press (astro-ph/0103328)